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ABSTRACT

The major task in solving a physics problem is to construct an appropriate model of the problem in terms of physical principles. The functions performed by such a model, the information which needs to be represented, and the knowledge used in selecting and instantiating an appropriate model are discussed. An example of a model for a mechanics problem is presented. A set of problem-analysis rules has been written which can construct physical representations for such problems. The rules are written in MRS, a representation and inference language which provides the features of first-order logic while allowing specification of Lisp implementations for data storage and inference methods, as well as allowing meta-level reasoning about the problem-solving process itself. The rules infer important features of the problem in small steps, which in turn trigger other inferences, in a fashion similar to the progression of inferences presented in the example problem. In this way, a finite set of rules serves to analyze a large set of possible problems. The physical model generated by the rules not only can drive generation of equations to solve the problem, but also can be used to generate meaningful diagrams and explanations of the problem-solving process. (Author/JN)

Model Formulation for Physics Problem Solving[1]

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Abstract

The major task in solving a physics problem is to construct an appropriate model of the problem in terms of physical principles. We discuss the functions performed by such a model, the information which needs to be represented, and the knowledge used in selecting and instantiating an appropriate model. An example of a model for a mechanics problem is presented.

1. Introduction

A physics problem is solved by modeling the real-world objects and interactions of the problem with idealized "physics" objects and interactions whose behavior is governed by physical laws. We have argued elsewhere [13] that a problem solver cannot simply select equations which superficially relate the variables of the problem and "plug in" the appropriate values (though novices often work this way), but instead must consciously decide how to model the objects and their relationships for the problem at hand. Equations, in fact, only have meaning with respect to an underlying model. For example, when the problem solver writes the equation "f = ma", he is (whether he realizes it or not) implicitly declaring that the speeds involved are low enough for relativistic effects to be unimportant, that there are no other significant forces on the body, and that the force and acceleration are measured relative to the same inertial reference frame. Larkin, McDermott, Simon, and Simon [7] have proposed that skill in selecting appropriate models is much of what is meant by the commonsense notion of "physical intuition". Larkin [8] has found that physics experts spend time selecting and filling out physical models before writing any equations. In a task of sorting physics problems into piles of "similar" problems, Chi et al. [1] found that experts sorted problems on the basis of

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"deep structure" similarities (i.e., the appropriate physical models for solving the problems), while novices sorted on the basis of surface similarities (e.g., "problems involving pulleys"). de Kleer [5] has pointed out the importance of "envisionment" in analyzing the behavior of objects in dynamics problems and in understanding physical mechanisms [6].

There is thus ample evidence that selecting the appropriate way of modeling a problem is the key task in solving problems in physics and related areas. We have previously written a program which can solve problems in the limited area of rigid body statics [11] [12], and believe that solving a problem is relatively easy once the appropriate physical models have been constructed. Our current research therefore concerns the task of constructing appropriate physical models for problems which may involve a variety of conditions and physical principles. The key research questions include:

- What should be the content of a physical model?
- How can a physical model be constructed from an informal problem statement?
- How can the desired solution be found from the physical model?

2. Contents of Physical Representations

The physical model should explicitly contain several features which have been implicit in earlier systems, including our own. First, the general environment in which the problem occurs should be represented (e.g., the surface of the earth, interplanetary space, an atomic nucleus). This is important both because features of the environment may be referenced by the problem without being explicitly mentioned (e.g., the earth-surface environment contains a ground plane and a constant gravitational acceleration towards it) and because the environment helps determine which physical principles are relevant (e.g., electrostatic forces between planets are unimportant, as are gravitational forces between subatomic particles).

Coordinate systems are particularly important, as shown by the large number of such systems in common use and the effort expended in teaching them; they are also one of the more observable artifacts of human problem solving, since they appear explicitly or implicitly in most diagrams. In addition to relating positions to a common geometric framework, coordinate systems frequently involve symmetry transformations (which reduce the dimensionality of the geometry which is used) and achieve invariants which simplify later problem solving (e.g., by making initial values zero and making important motions vary in only a single coordinate dimension).

Physical quantities may be expressed in various units, may be expressed relative to different frames of reference, and may vary with time. Unknown factors frequently need to be defaulted or made into variables by the problem solver, and known quantities may need to be masked (e.g., when the problem requests calculation of the speed of light based on an experiment). The need to represent these factors has long been recognized [10], and some of them have been represented in earlier systems [5] [2].

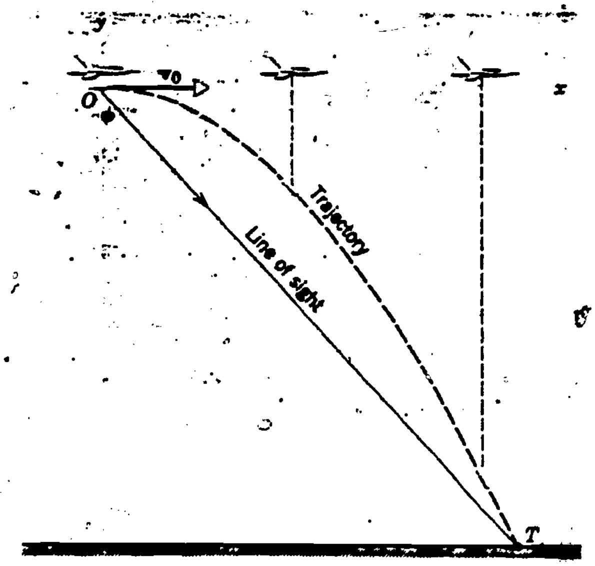
3. Creation of Physical Representations from Informal Descriptions

How can an informal description of a problem (i.e., the understanding of the problem which a layman might have after reading the problem statement) guide the construction of an appropriate physical model? One approach would be schema matching [9]; however, we do not consider this approach viable, both because of the computational difficulty of graph matching and because of the large number of schemata which would be required to achieve robust competence. The problem of constructing a "physics deep structure" for a problem is in many ways similar to the problem of parsing natural language sentences. Just as parsers attempt to cover an infinite number of possible sentences with a finite set of grammar rules, a problem solver attempts to cover an infinite set of possible problems with a finite set of physics rules. Physics problems require the resolution of implicit reference to unmentioned objects (e.g., the ground) based on world knowledge of typical relationships. The model for a complete problem ("sentence") will be composed of submodels for parts of the problem ("phrases"); a higher-order model imposes constraints on the subordinate models which compose it. Unfortunately, physics lacks the constraints which linear word order imposes on interpretation of natural language.

4. An Example

Consider the following problem ([4], p. 57):

> A plane is flying at a constant horizontal velocity of 500 km/h at an elevation of 5.0 km toward a point directly above its target. At what angle of sight φ should a survival package be released to strike the target?



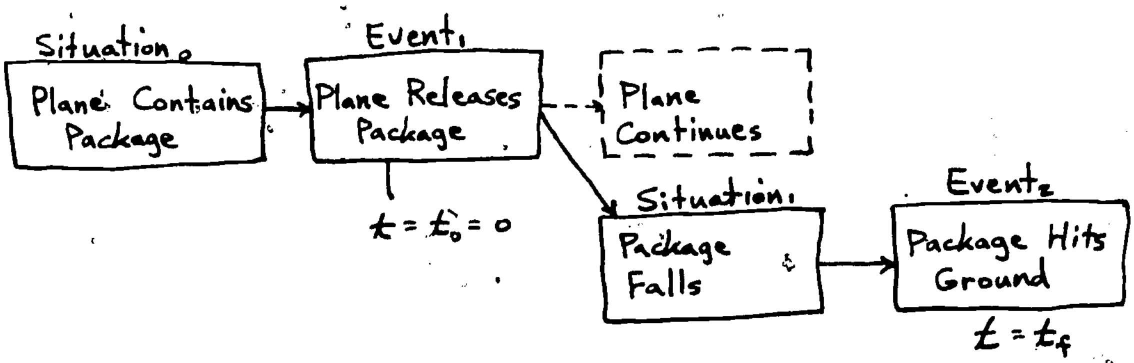
The figure (from [4]) illustrates a number of decisions which have been made in constructing the physical model. There are two directions which are important in this problem: horizontal (because the plane and package have horizontal motion) and vertical (because the package falls downward) with respect to the surface of the earth (which is always the implied environment for an airplane in flight). Therefore, the coordinate system which is chosen is a vertical plane containing both of these directions of motion. The coordinate system is aligned so that important features (the initial position of plane and package and the time of release of the package) have the value zero. The ground (unmentioned in the problem statement) is inferred to be the location of the target and the termination point of the falling of the package; the time of impact is the ending time for the problem. Once all of these representation decisions have been made, retrieval of the appropriate equations and solution of the problem are relatively easy.

5. Automatic Construction of Physical Representations

We have written a set of problem-analysis rules which can construct physical representations for problems such as the example above. The rules are written in MRS [3], a representation and inference language which provides the features of first-order logic while allowing specification of Lisp implementations for data storage and inference methods, as well as allowing meta-level reasoning about the problem-solving process itself. The rules infer important features of the problem in small steps, which in turn trigger other inferences, in a fashion similar to the progression of inferences in the descriptive paragraph above. In this way, a finite set of rules serves to analyze a large set of possible problems.

5.1. Representation of Situations and Events

The representation which is used for time is a partial order of Situations connected by Events. A Situation is a period of time during which conditions do not change in some sense, while an Event is a time point at which a significant change occurs. Variable values may change during a situation (e.g., a body may be falling during the situation). A Situation is not a feature of the real world, but is an artifact of the problem solver, like a coordinate system: it is a way of looking at certain objects during a period of time for a particular problem-solving purpose. The separation of time into Situations and Events has several benefits. First, it corresponds well to informal ways of describing problems. Second, inferences which can be made from this representation allow the problem solver to complete an underspecified problem statement. In the example problem above, for example, the release of the survival package by the plane is an Event which generates a number of useful inferences: there must be a Situation preceding the release in which the plane is holding the package; in this Situation, the velocity and position of the package must have been the same as that of the plane; in the following situation the package will be falling; since falling cannot continue indefinitely in an earth-surface environment, there must be a collision Event which terminates the falling Situation, and whose default location is the ground. Finally, there are physical principles which apply to Situations and Events: position of an object is continuous across an Event, and velocity is continuous unless the Event involves a collision; the laws of uniform motion and uniform acceleration apply across the falling Situation. The Situation-Event sequence for the example problem is as follows:



6. Summary

We have illustrated how a set of problem analysis rules can be used to translate an informal description of a physics problem into a physical model "deep structure". We believe that a parser derived from that of ISAAC [12] can generate from an English problem description the sort of informal problem description used as input to these rules. The physical model generated by the rules not only can drive generation of equations to solve the problem, but also can be used to generate meaningful diagrams and explanations of the problem solving process.

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